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A Preliminary Measurement of Hadronic Mass Moments in Semileptonic B Meson Decays

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A preliminary measurement of the second moments of the hadron mass in $B \to X\ell\nu$ decays by the *BABAR* Collaborations is reported. These measurements are performed as a function of the lepton momentum above a given threshold.

For many years semileptonic decays have been the topic of a large variety of studies because they are theoretically simple at the parton level, sensitive to the coupling of quarks to the weak charged current, and allow us to probe the impact of strong interactions on the bound quark. Experimentally they are readily accessible, because of the large branching fraction and clear signature in form of a high momentum lepton. The principal goal for studies of semileptonic B meson decays is the determination of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$.

The decay width for inclusive semileptonic B decays to the charm states X_c can be written as

$$\Gamma^c_{SL} \equiv \mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu})/\tau_B = \gamma_c |V_{cb}|^2, \qquad (1)$$

i.e., $|V_{cb}|$ can be determined from the branching fraction and the average B lifetime, provided the factor γ_c is known. The theoretical QCD parameter γ_c requires both perturbative and non-perturbative input. In the framework of Heavy Quark Effective Theory the uncertainties in the estimate of γ_c can be reduced by using information from other inclusive measurements, for instance, the moments of the mass distribution of the hadrons X_c. Like the total decay rate, this inclusive observable can be calculated using expansions in powers of the strong coupling constant $\alpha_s(m_b)$ and in inverse powers of the B meson mass, m_B, that include non-perturbative parameters. At order $1/m_B^2$, there are three parameters, $\bar{\Lambda}$, λ_1, and λ_2. From the $B^* - B$ mass splitting, we have $\lambda_2 = 0.128 \pm 0.010\,\mathrm{GeV}^2$.

In the following, we report a preliminary measurement performed with the *BABAR* detector [1] operating at the $\Upsilon(4S)$ resonance at the PEP-II energy asymmetric e^+e^- storage ring [2] at SLAC. This measurement of the second moment of the hadron mass distribution as a function of the minimum lepton momentum was first reported last summer [3]. An update of this measurement is expected for this summer's conferences.

We measure the second moment of the invariant mass M_X distribution of the hadronic system X in $B \to X\ell\nu$ decays, $\langle M_X^2 - \overline{m}_D^2 \rangle$, where $\overline{m}_D = (m_D + 3m_{D^*})/4 = 1.975$ GeV/c^2 is the spin-averaged D meson mass. This measurement is similar to one performed by CLEO [5].

The analysis is based on a sample of 55 million $B\overline{B}$ events, from which we select a subsample of 5,800 events (above a background of 3,600 events that are statistically subtracted using the energy constrained B mass distribution). In these events one B meson is fully reconstructed in a hadronic decay mode and the semileptonic decay of the second B is identified by a high momentum electron or muon. The system X in the decay $B \to X\ell\nu$ is made up of hadrons and photons that are not associated with the B_{reco} candidate. We exploit the available kinematic information of the full $B\overline{B}$ event by performing a 2C kinematic fit that imposes four-momentum conservation, the equality of the masses of the two B mesons, and forces $M^2_{miss} = M^2_\nu = 0$. The fit takes into account event-by-event the measurement errors of all individual particles and the measured missing mass. This leads not only to a significant improvement of the r.m.s. of the mass resolution of the X system but also provides an almost unbiased estimator of the mean M_X and a resolution that is largely independent of M^2_{miss}.

Figure 1 shows the resultant M_X distribution of the selected events, for a minimum lepton momenta $P^*_{min} = 0.9\,\mathrm{GeV}/c$. Different $B \to X_c l\nu$ decays contribute to this distribution. The dominant decays are $B \to D^* l\nu$ and $B \to Dl\nu$, but we also expect contributions from decays to higher mass charm states, D^{**} resonances with a mass distribution X_H^{reso} peaked near 2.4 GeV/c^2, and potentially non-resonant $D^*\pi$ final states

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for which we assume a broad mass distribution X_H^{nreso} extending to the kinematic limit. The background is dominated by secondary semileptonic charm decays, contributions from lepton (primarily muon) misidentification are much smaller. The backgrounds decrease significantly for higher P^*_{min}.

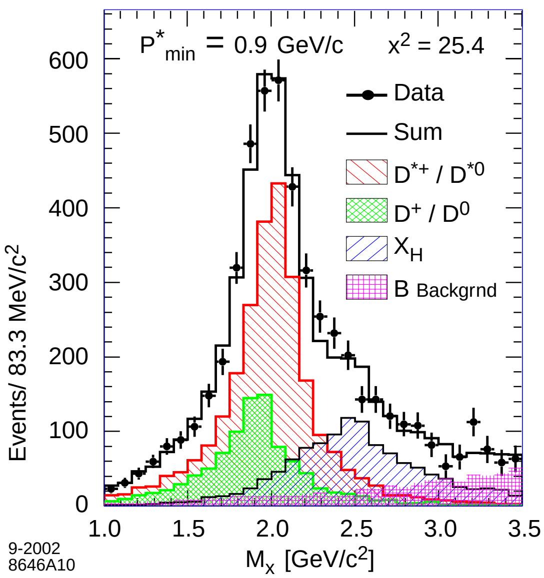

Figure 1. The measured M_X distribution for $P^*_{min} = 0.9\,\mathrm{GeV}/c$. The hatched histograms show the fitted contributions from $B \to D^* l\nu$, $B \to Dl\nu$ and $B \to X_H l\nu$ decays, as well as the background distribution. The white histogram represents the sum of all the individual distributions.

A binned χ^2-fit to the M_X distribution is performed to determine the relative size of the three signal contributions, f_{D*}, f_D, and f_{X_H}, where f_{X_H} refers to the sum of the resonant and non-resonant high mass charm states. Taking into account the true particle masses (the D and D^* masses are basically δ functions, and the mean of the X_H contribution is taken from generated events) the second moments are calculated according to the following expression

$$\begin{aligned} \langle M_X^2 - \overline{m}_D^2\rangle &= f_{D^*}\cdot(M_{D^*}^2 - \overline{m}_D^2) \\ &\quad + f_D\cdot(M_D^2 - \overline{m}_D^2) \\ &\quad + f_{X_H}\cdot\langle M_{X_H}^2 - \overline{m}_D^2\rangle. \end{aligned} \tag{2}$$

Figure 2 shows the second moment as a function of the lepton momentum above a minimum P^*_{min}. The increase at lower momenta is attributed to contributions from the high mass states, i.e. the non-resonant X_H^{nreso} decays. The CLEO Collaboration has measured the same moment for $P^*_{min} = 1.5$ GeV/c, based on similar assumption about the high mass hadronic states. Their result [5] is in good agreement with the measurement presented here. The data are also consistent with a measurement by the DELPHI Collaboration [6] that corresponds to $P^*_{min} = 0 GeV/c$.

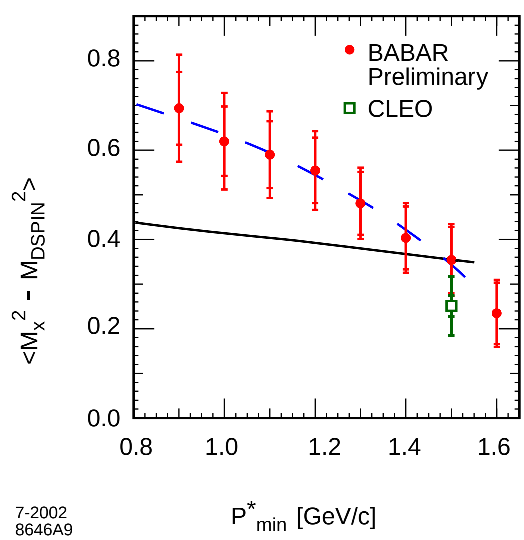

Figure 2. Measured mass moments as a function of the minimum lepton momentum, P^*_{min}. The errors indicate the sum of the statistical and systematic uncertainties, they are highly correlated. The dashed curve shows the best description of the data by the OPE expansion [7] with λ_1 and $\bar{\Lambda}$ as free parameters. For comparison, the solid line shows variation of the moments for the parameters $\lambda_1 = -0.17$ GeV^2 and $\bar{\Lambda} = 0.35$ GeV [8].

Extensive studies have been performed to assess the systematic uncertainties and potential biases in the moment measurement. These studies involve both changes in the event selection and variations of the corrections for efficiencies and resolution, and comparisons of data with Monte Carlo simulations. The leading systematic error is due to the uncertainty in the model for the higher mass states X_H. Other errors are due to uncertainties in the Monte Carlo simulation of the detector resolution and efficiencies as well as in the background contributions.

As one of the many cross checks we use the relative contributions f_i to determine branching fractions by correcting for acceptance and setting the total semileptonic branching fraction to 10.87%. The resultant partial branching fractions are fully compatible with previous measurements and independent of P^*_{min}. This is also the case when we split the X_H contribution into a resonant and non-resonant part and allow both of them to vary independently.

Heavy Quark Effective Theory (HQET) calculations of the second mass moment $\langle M_X^2 - \overline{m}_D^2\rangle$ have been carried out [7] using Operator Product Expansions (OPE) up to order $\alpha_s^2\beta_0$ and $1/m_B^3$. These expansions

contain the non-perturbative parameters $\bar{\Lambda}$ ($\mathcal{O}(m_B)$), λ_1 and λ_2 ($\mathcal{O}(m_B^2)$). The observed dependence of the moments on the minimum lepton momentum can be reproduced, as long as we adjust the non-perturbative parameters.

If we restrict the data to $P^*_{min} = 1.5\,\mathrm{GeV}/c$ and use a recent, independently measured value of $\bar{\Lambda} = 0.35 \pm 0.08 \pm 0.10$ GeV [8], we obtain $\lambda_1 = -0.17 \pm 0.06 \pm 0.07\,\mathrm{GeV}^2$, a result that is in good agreement with the CLEO value of $\lambda_1 = -0.236 \pm 0.071 \pm 0.078\,\mathrm{GeV}^2$. However, if we take this value of λ_1 and $\bar{\Lambda} = 0.35\,\mathrm{GeV}$ and calculate the moments as a function of P^*_{min}, we find a much smaller momentum dependence than the data indicate (see Figure 2).

In summary, if the assumption is correct that there are significant contributions from charm states with masses extending well beyond the resonance D^{**}, the second moment is expected to rise for lower lepton momenta, an effect that is not described by OPE using other independently measured values of the parameter $\bar{\Lambda}$. On the other hand, we currently do not have adequate knowledge of the branching ratios and mass distributions for higher resonant and mass resonant states in semileptonic B decays. And their contribution and mass distribution enter critically into the method that has been applied to extract the mass moments. It is expected that more direct methods to measure moments will reduce this dependency. Results are expected in the near future.

Probably the best way to address this problem, is to perform more detailed measurements of various exclusive semileptonic branching fractions for decays to higher mass states. In addition, we expect to improve the method of determining moments, to measure higher mass moments, and to add moments of the lepton energy spectrum. Measurements of the inclusive photon spectrum in $b \to s\gamma$ will also add critical information on the nonperturbative effects that have impact on the translation of inclusive decays rates to $|V_{cb}|$, and $|V_{ub}|$.

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